Cannibalism, altruism and trophallaxis strategies among self-sustainable swarm robots

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Abstract: Energy sourcing and usage is a critical component in environmental swarm robotics. Populations of autonomous agents must gather energy from the environment and decide how to distribute it amongst themselves. Determining the optimum strategy for energy management across the swarm, with respect to the high-level goal of the population, remains a challenge. In this paper we explore three bio-inspired energy transfer strategies for self-sustainable swarm robots: Trophallaxis, Altruism and Cannibalism and build a simulation to evaluate the optimal strategy. Decentralised robot agents traverse a bounded environment and undertake terrain detection and food exploration tasks and the total rating of each simulation is recorded as a measure of mission success. Statistical results indicate that dynamic energy transfer can affect the performance of swarm robots significantly, with cannibalism and altruism being suitable for terrain coverage and trophallaxis being best for urgent tasks. This work shows the importance of implementing energy sharing strategies for a wide range of swarm applications, and the suggests that the optimal collaboration strategy is heavily influenced by the specific task goal.

Keywords: Swarm robot, Swarm intelligence, Artificial life

1 INTRODUCTION

Swarm robotics, in contrast to conventional centrally controlled robots, enables complicated tasks to be conducted through the collaboration of populations of robots and the emergence of novel behaviours [1]. During the operation of swarm robots, each robot operates as a separate agent where communication and signal processing are conducted by low-cost embedded sensors and controllers [2]. Typically, energy is provided through one-time or rechargeable batteries, requiring return-to-base when energy is low. A better approach is to restore energy by the self-sustainable consumption of energy-rich matter available within the environment [3]. In this paper, the optimal collaboration strategies of a self-sustainable robot swarm with waste and food digesting systems were investigated and evaluated. We take inspiration from the prototypes, EcoBot-III [4] and Row-bot [5], which employ embedded Microbial Fuel Cells (MFCs) [6] to scavenge energy from the surroundings, consume the biomass as fuel and exhaust the biodegradable waste [7]. These attributes enable a new generation of self-sustainable robots. In addition to gathering environmental energy, we consider the strategic transfer of energy between robots, which may be critical to the high-level mission of the swarm. Through simulation, we evaluate optimal strategies for robot interactions and energy transfer, including trophallaxis, altruism and cannibalism.

In the presented simulation, robots traverse a bounded environment and undertake a task of terrain detection (map covering) and food exploration. A set of prototype rule-based robot locomotion and collaboration scenarios were modelled, demonstrating three different kinds of interaction strategies: Trophallactic robot swarms are defined as having individual robots which will voluntarily share their energy equally with any lower-powered robot they encounter. Altruistic robots will retain the essential energy needed to travel back to the starting position and will donate their remaining energy to the robot they meet. In contrast, robots may adopt the most aggressive cannibalism strategy, where individuals will take all the energy from a neighbouring robot, leaving the other robot with zero remaining energy. In this case, we assume the deceased robot is bio-degradable and will not cause damage to the environment. The processes of validation and evaluation of the three robot swarm scenarios are as follows:

1. Optimisation of simulation, including environment formation, robot locomotion, food detection and robot collaboration.
2. Evaluation of each robot swarm strategy, comparing the performance in map detection and covering rate between self-sustainable robots and conventional (non-sustainable) robots, with different robot energy levels and varied population size.
3. Assessment of the statistical performance of the three collaboration strategies (altruism, trophallaxis and cannibalism), in aspects of area coverage speed, maximum

displacement, the amount of food consumed, and information retrieved.

2 METHODS

The simulation is constructed and operated through MATLAB [8]. The environment and robot agent are first defined and detailed features and factors are applied and explored for optimising and evaluating robot performance.

2.1 Environment and Robot Definition

We first represent the environment by a bounded 2D discretised grid, where each robot will start from the robot base and traversed under specific rules. The distance is measured by Chebyshev distance [9] so that the cost of diagonal moving is the same as horizontal and vertical moving. The biomass is randomly distributed on the map and consumed by the mobile robot. The factors for an energy-rich environment as follows:

$$Env: \{Ex, Ey, Ecx, Ecy, Bn, Bv\} \quad (1)$$

Where *Ex* is the number of cells in the x-axis, *Ey* is the number of cells in the y-axis. *Ecx, Ecy* is the location of robot base, located at the origin by default. *Bn* is the number of biomass units in the environment, and *Bv* is the value of energy offered for each biomass.

We define a N*M matrix to represent each time step in the environment. Where N is the number of robot agents, and M is the number of factors used to define each robot. Therefore, we have,

$$Robot: \{Rx, Ry, Re, Rs, Ra\} \quad (2)$$

as factors to represent the robot state. Where *Rx* is the real-time location of the robot in the x-direction, *Ry* is the location in the y-direction and *Re* is the energy remaining. *Rs* is in the range [1, N] and defines the position of the robot in the sequence when evaluating actions at each step. *Ra* represents the current state of the robot, {active, inactive}. The robot will become inactive if it runs out of energy or is eaten by another robot under the cannibalism strategy.

2.2 Robot Locomotion and Collaboration

After configuring the environment and robots, rules are applied to regulate each robot agent's behaviours and therefore to simulate the multiagent system. We define a range of rules for locomotion, sustainability, return-to-base and collaboration in the following sections.

2.2.1 Locomotion

To reduce computational requirements, a simple algorithm for terrain detection is implemented. An individual robot will move to an unvisited cell and mark it as visited. The sensing range is a 5×5 square grid. One of three rules are applied depending on the local environment:

1. Randomly move one distance when the whole 25 cells have been marked as visited.
2. Randomly choose one untravelled cell among the eight nearby cells if there are untravelled cells within one distance, then move to this point.
3. Randomly choose one untravelled cell among 16 peripheral points if all eight neighbouring cells are marked as visited and peripheral points have untravelled points, then move towards this point by one cell.

2.2.2 Self-sustainable vs Non-sustainable

A robot is defined as self-sustaining if it gathers energy from the environment. It is defined as non-sustaining if all its energy is provided at the start and cannot gather more energy from the environment. A self-sustaining robot detects (or smells) food in nearby cells and moves towards them when the intensity is above a threshold *T*. The robot calculates the odour intensity *I* of the eight nearby cells. The intensity I_p of cell *p* is calculated by the sum of detectable signals,

$$I_p = \sum_{k \in (A)} S_k \quad (3)$$

where *A* is the set of nearby cells where intensity is higher than *T*, and the relative intensity S_n of point *p* from food unit *n* is,

$$S_n = \frac{100}{{d_{p,n}}^2} \quad (4)$$

where $d_{p,n}$ is the distance between point *p* and biomass *n*. The robot will move to the nearby point with the highest intensity *I* until it encounters food.

2.2.3 Return to Base

Under normal circumstances, robots will return to the base at the end of their mission and prepared for future deployment. An individual will decide to return to base when the energy drops to a critical level. It will first compare the minimum energy needed to return to base, equivalent to the maximum real-time displacement Max{*Rx*, *Ry*}, and the remaining energy *Re*. When *Re* - Max{*Rx, R*} ≤ 1, the robot initiates the return process. When returning, the robot will search for the best route, while executing terrain detection and biomass exploration tasks, but they can only move towards the starting point. This guarantees that robots can return to origin.

2.2.4 Collaboration

Three different collaboration strategies are explored: Trophallaxis, Altruism and Cannibalism.

Trophallactic robots adopt the most egalitarian strategy to complete the task. When a robot loses half its energy, it is then marked as a low-energy robot. A low-energy robot will keep work towards accomplishing the task but can be helped by high-energy robots. When a low-energy robot encounters a high-energy robot, the low-energy robot will receive the energy until they have the same energy.

The altruistic strategy aims to accomplish the task with fewer robot deployed and to ensure all robots can return to base. In this strategy, if a high-energy robot encounters a low-energy robot, the low-energy robot will pass all its energy to the high-energy robot, preserving just enough energy to enable it to return to base.

Cannibalism is a more effective but more ruthless strategy than altruism. When a high-energy cannibal robot meets a low-energy robot, it takes all the energy from the low-energy robotic, leaving it inactive (or deceased). We assume the deceased robot is bio-degradable and will not cause damage to the environment.

These three genres of robots are deployed in separate simulations, with each simulation repeated 1000 times to obtain robust statistical results. We consider performance metrics including area coverage speed (total terrain information detected over total steps), maximum displacement, the amount of food consumed, and information retrieved. Finally, a simulation is also run for non-interacting robots to provide a base for statistical comparison.

3 RESULTS

3.1 Self-sustainable vs Non-sustainable

We firstly compared the self-sustainable robots and non-sustainable robots by varying the initial energy. The environment is set to Env = {101, 101, 0, 0, 40, 20}, and there are 10 robots undertaking the exploration task. For self-sustainable robots, a threshold T of 10 is applied for the biomass detection task. Fig.2 shows the mean map cover (terrain detection) comparison of self-sustainable and non-sustainable robots by varying the amount of energy distributed in the environment in the range [10, 200] with an interval of 10. Each point in Fig.2 is the mean of 100 simulations. The figure shows that self-sustainable robots result in higher map coverage, and the difference monotonically increases with rising initial energy loaded: 14.1% more terrain is discovered with initial energy of 10, and this increases to 19.8% with initial energy of 200. The amount of biomass collected is also recorded, and the fit function is shown in eqn.5 below.

$$y = 0.009745x + 0.1243 \tag{5}$$

Where y is the estimated number of biomass collected by one robot and x is the initial energy of the robot.

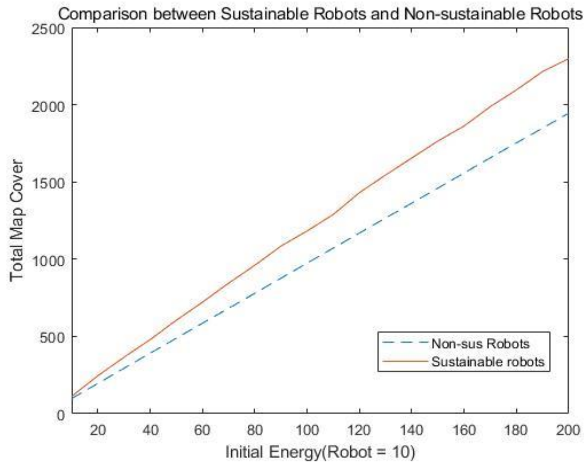

Fig. 2. Map cover comparison between self-sustainable and non-sustainable robots for initial energy in the range [10, 200].

A second simulation to compare self-sustainable and non-sustainable robotics was run, where the number of robots was varied in the range [10,200] with interval 10. Initial environmental energy was fixed at 50. Fig.3 compares map coverage between self-sustainable and non-sustainable robots for different population sizes. The figure shows that self-sustainable robots deliver higher map coverage until 70 robots are deployed, above which non-sustainable robots are more effective. Ten self-sustainable robots explored 24.1% more terrain information than ten non-sustainable robots, whereas 200 non-sustainable robots obtained 24.5% more terrain information than 200 self-sustainable robots. It is estimated that each robot can obtain 0.62 biomass when there are 10 robots, and the number drops to 0.15 for a robot group size of 200.

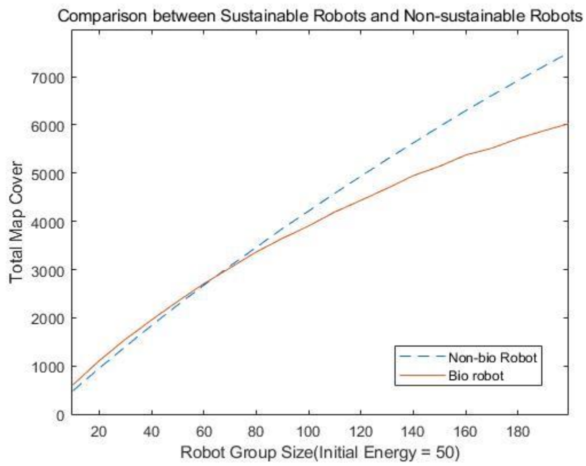

Fig. 3. Map cover comparison between self-sustainable and non-sustainable robots robot group size in the range [10, 200]. Initial energy was 50 for each robot group size.

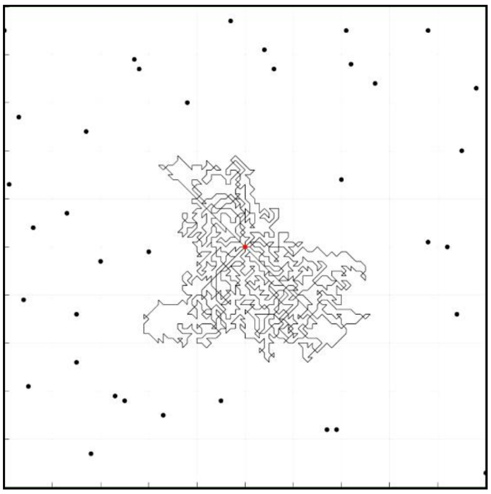

Fig. 4. The route of trophallactic robots, robot group size =10, initial energy = 100, *Tr* = 25 and *Tb* = 10.

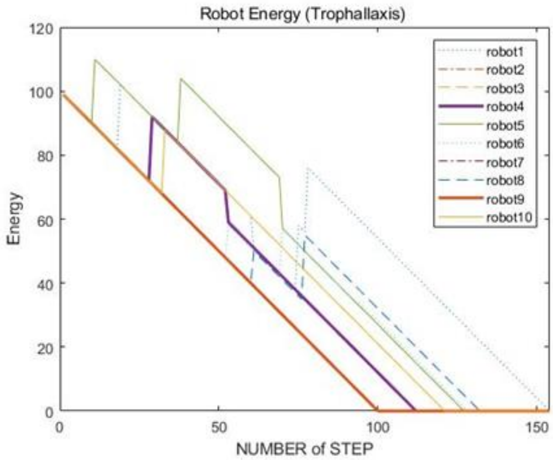

Fig. 5. The energy variation of trophallactic robots, robots will voluntarily share their energy equally with lower-powered robots they encounter.

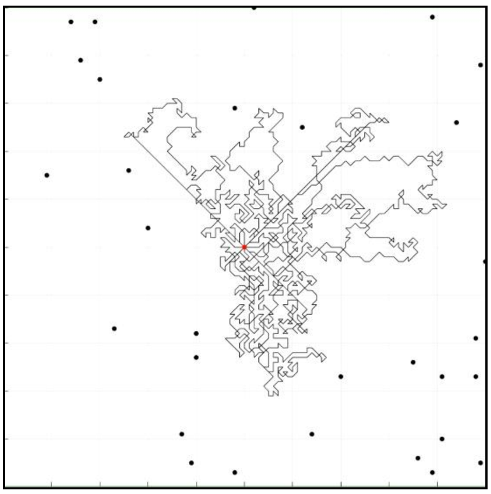

Fig. 6. The route of altruistic robots, robot group size =10, initial energy = 100, *Tr* = 25 and *Tb* = 10.

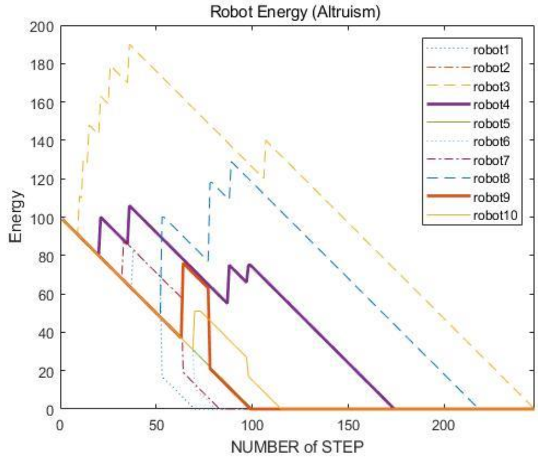

Fig. 7. The energy variation of altruistic robots, robots will retain essential energy needed to travel back to the starting position and donate the remaining energy to a neighbour.

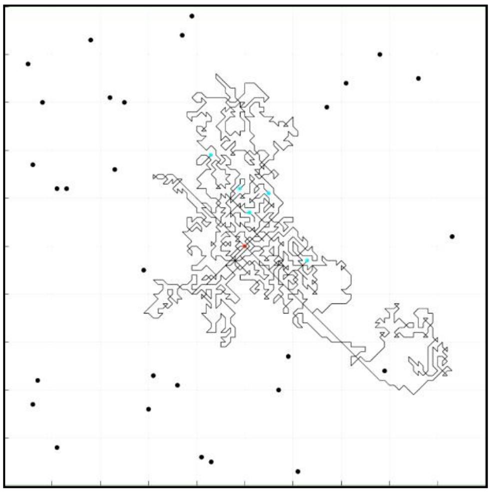

Fig. 8. The route of cannibal robots, robot group size =10, initial energy = 100, *Tr* = 25 and *Tb* = 10. Blue dots are deceased robots.

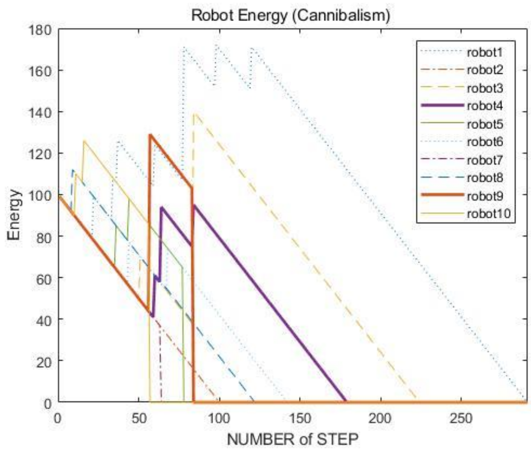

Fig. 9. The energy variation of cannibal robots, robots will rob all the energy from the encountered robot.

3.2 Robot Collaboration Strategies

To illustrate the difference in collaboration strategy, we record sample runs for each collaboration strategy, as shown in Fig.4, Fig.6 and Fig.8. These show routes of each robots, with the corresponding real-time energy variations of individual robot showed in corresponding Fig.5, Fig.7 and Fig.9. Ten robots with 100 initial environmental energy traverse the environment $Env = \{101, 101, 0, 0, 40, 20\}$. The biomass detection threshold Tb = 10 and robot detection threshold Tr = 25. For the cannibal history route map (Fig.8) deceased robots are marked as blue dots.

We compared the performance of the three collaboration strategies, and the case of no collaboration strategy, in aspects of discovering speed, maximum displacement, number of biomass and terrain information retrieved. These are shown in Figs.10, 11, 12, 13 for robot group size 50. In these box plots, central lines indicate the median, top and bottom box edges indicate the 1st and 3rd quartile. Whiskers are extreme data without considering outliers. Outliers are marked with '+' symbols. [10]

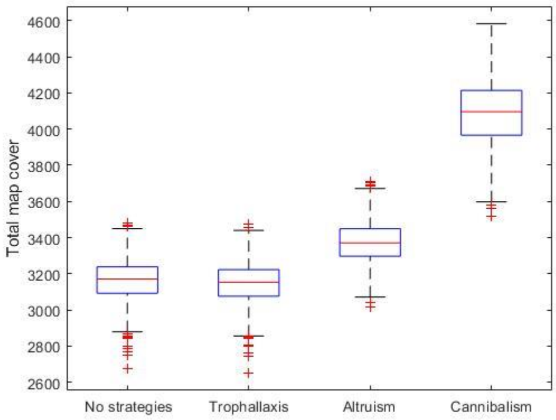

Fig.10 Box plot of total map coverage.

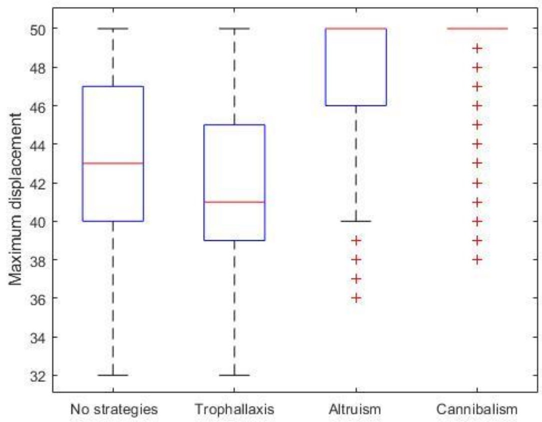

Fig.11 Box plot of maximum displacement comparison.

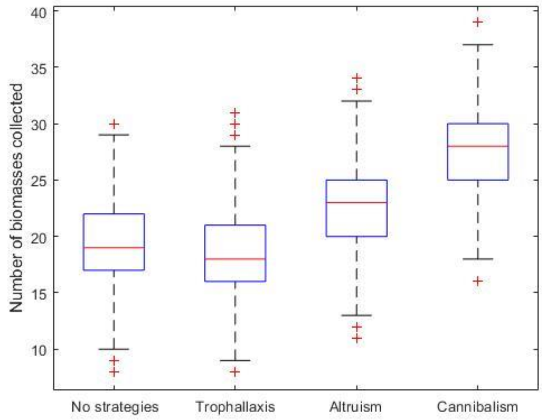

Fig.12 Box plot of biomasses collection comparison.

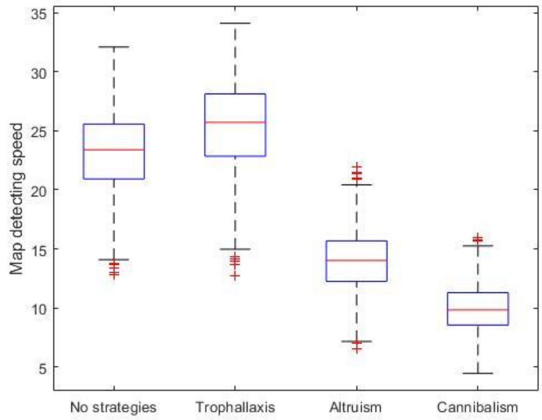

Fig.13 Box plot of map covering speed comparison. Speed is unique points visited per time step.

4 DISCUSSION AND CONCLUSIONS

These simulations indicate the potential of self-sustainable swarm robots and the importance of dynamic energy exchange among robots.

By comparing self-sustainable robots and non-sustainable robots, we show that utilising environmental biomass can deliver a better performance under a fixed robot group size. Self-sustainable robots exhibit significant advantages until the number of robots saturates the available environmental energy. When a small number of robots explore a relatively energy-rich environment, they benefit from the ready availability of the food and energy collection does not interfere with the goal of spatial exploration. If, however, a large number of robots explores a relatively barren environment, they may prioritise energy collection over exploration, limiting mapping performance. This suggests the optimum robot group size is related to the available energy of environment. These self-sustainable swarm robots show advantages in tasks such as cleaning oil-polluted zones and exploring energy-rich environments.

Simulations and energy profiles (Figs. 4-9) reveal the characteristics of three robot collaboration strategies. Trophallactic robots share, and hence normalise, energies. This results in a dense region of exploration round the origin, since no robot can gather significant energy to explore more widely before having to return to base. Altruistic robots produce more energetic robots, enabling them to undertake longer journeys for terrain exploration. Cannibal robots can achieve the highest energies, and hence explore more widely than altruistic robots, but at the expense of some dead robots. As a result of these loses, we suggest that the cannibal robots should be bio-degradable and low cost.

Statistical analysis of key performance metrics showed that energy transfer strategies significantly affect the performance of the swarm robots (Figs. 10-13). The trophallactic robot swarm completes the same task with 10% less time taken than other strategies. An increase of 20% to 30% in terrain exploration is observed by implementing the cannibalism strategy, and 10% to 15% for swarms with the altruism strategy. Higher performance in environmental energy collection is also observed for altruistic robots and cannibal robots. Maximum displacement (Fig.11) indicates that altruistic robots and cannibal robots can easily reach the environment boundary and could explore even larger environments. The trophallaxis strategy showed the highest suitability for urgent tasks, while altruism guaranteed a higher exploratory area and food collection without any robot losses. The cannibalism strategy resulted in the highest food collection and map coverage, but coverage speed was much lower than altruism and trophallaxis, suggesting that cannibalism is most suited to large-scale and non-time-critical scenarios. The results show that robotic altruism, trophallaxis and cannibalism are important energy sharing strategies for a wide range of swarm applications.

This simulation is intended to offer an overview of a range of bio-inspired energy sharing methods, indicating the potential and importance of robot collaboration. However, the study is still in the early stage and findings are based on a constrained 2D simulation. The simulation will be updated in parallel with our parallel research in practical altruistic and cannibalistic swarm robots.

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